Variations in the Branching Pattern and Dimensions of Arch of Aorta

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CERTIFICATE

This is to certify that this dissertation entitled **"Variations in the Branching Pattern and Dimensions of Arch of Aorta"** is the bonafide record of work done by **Dr. N. Isai Vani** under my guidance and supervision in the Department of Anatomy during the period of her postgraduate study for M.S. (Branch V) Anatomy from 2006 to 2009.

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Introduction

The normal aortic arch curves smoothly upward into the superior mediastinum, running from right to left and anterior to posterior , with its apex approximately at the mid manubrium. The most common right to left branching pattern of the aortic arch is brachiocephalic trunk, left common carotid and left subclavian artery. In the complete formation of the aortic arch and its branches, there is ample opportunity for anomalous development by persistence of certain embryonic vessels and disappearance of others. These may include anomalies pertaining to the arch per se., such as absent or double aortic arch, right aortic arch or anomalies of branching patterns such as common trunk for brachiocephalic and left common carotid artery, common trunk for left common carotid and left subclavian artery, vertebral artery or retroesophageal right subclavian artery as the fourth branch or combination of any of these.

Anomalous development of the aortic arch and its major branches becomes clinically significant when these vessels encroach upon and constrict adjacent mediastinal structures such as the esophagus and trachea, interfering with respiration and deglutition (dysphagia lusoria).[1,2] The various anomalies of the aortic arch and its branches are often associated with other congenital anomalies such as tetralogy of Fallot (ToF),[3,4] tricuspid atresia, truncus arteriosus, transposition of great vessels, ventricular septal defect (VSD),[5] pulmonary stenosis, double outlet right ventricle,[4] patent ductus arteriosus (PDA),[6] persistent trigeminal artery, persistent proatlantal segmental artery, tracheoesophageal fistula, anomalous right recurrent branch of vagus and right thoracic duct.[7] In

addition to congenital malformations, pathological aneurysms and obstructions can also occur.

Knowledge concerning the various anomalies of the aortic arch derivatives is important to the clinician, radiologist and surgeon who treat patients who have symptoms attributable to these anomalies. To the clinician and radiologist, this knowledge aids in evaluating the findings in cases in which symptoms may result from the presence of vascular anomalies. To the surgeon, realization of the possible vascular configurations which may interfere with the function of either esophagus or trachea, will serve as a guide while exploring the region of the aortic arch and in determining the exact nature of the anomaly in a given case. This determination will serve to guide the surgeon to perform those procedures most suitable for the correction of the condition or for the relief of symptoms resulting from it. Improvements in the methods of opacification of the aorta and its branches leading to the exact diagnosis and localization of arterial and aortic lesions have kept pace with the advances in vascular surgery, the proper interpretation of which requires an awareness of these variations.[8]

Knowledge of dimensions of the aorta and its major branches assumes great importance in cardiovascular surgical and stenting procedures. Attempts at stenting in cases of anomalous aortic arches were associated with increased failure rates and neurological complications.[9] And in such cases the surgical approach may have to be changed from the usual femoral to a brachial approach.[10] Dissecting aneurysm is more common when the vertebral artery arose directly from the aortic arch.[11] In endovascular repair of aortic dissection,

aortic arch is the proximal landing zone and the diameter of the stent-graft is decided only according to the diameter of the aortic arch.[12]

A thorough knowledge of the aortic arch, variations of its branching pattern and its dimensions is therefore necessary for the accurate diagnosis and proper management of the various disorders associated with these anomalies. Even though the variations in branching pattern and anomalies are documented in the literature, not much is known about the dimensions of the normal as well as the anomalous branches. This study is therefore undertaken to shed more light on the dimensions and variations of the aortic arch and its branches.

Aims & Objectives

1. To study the anatomical variations in the branching pattern of arch of aorta in cadaveric specimens by gross dissection.

2. To measure and analyse the variations in the dimensions of normal and variant aortic arch and its branches.

Review of Literature

I. Arch of aorta

1. Normal anatomy

1.1. Extent

1.2. Course

1.3. Relations

1.4. Branches

1.5. Dimensions

1.6. Radiological anatomy

2. Variations

2.1. Embryology

2.2. Anomalies of the arch

2.3. Anomalies of branching pattern

3. Clinical significance

3.1. Historical perspective

3.2. Surgical significance

3.3. Radiological importance

II. Casting:

1. History

2. Methods

3. Advantages

I. ARCH OF AORTA

1. Normal anatomy

The term “aorta” is derived from Greek ***aeiro,*** which means “to raise”. Anatomically, the aortic arch is defined as the segment of aorta between a line at a right angle proximal to the brachiocephalic artery origin and extending to a line drawn at a right angle distal to the left subclavian artery.[13]

1.1. Extent

The arch of aorta begins posterior to the right half of sternal angle as a continuation of ascending aorta. It ends by joining the descending aorta on the disc between fourth and fifth thoracic vertebral bodies, in the same horizontal plane as its origin.[14] Topographically, it is that part of aorta that rises above the plane dividing superior from inferior mediastinum. It lies in the superior mediastinum opposite to the lower half of mediastinum sterni.[15]

1.2. Course

The arch first ascends diagonally back and to the left over the anterior surface of trachea, then back across its left side and finally descends to the left of fourth thoracic vertebral body, continuing as the descending thoracic aorta. It ends in level with the sternal end of second left costal cartilage.[16] It curves around the hilum of left lung and its upper convexity reaches as high as the midpoint of manubrium sterni.[17]

1.3. Relations

The arch is convex to the left as well as upwards, that is, it is convex in two planes (Figure 1). Hence, the arch has 4 aspects[15] – left anterior, right posterior, concave lower. Five structures are related to the four aspects:

Right posterior aspect:

a) trachea

b) esophagus

c) left recurrent laryngeal nerve

d) thoracic duct and

e) vertebral column.

Left anterior aspect:

a) left lung and pleura

b) left phrenic nerve

c) left vagus nerve

d) cardiac nerves and

e) left superior intercostal vein

Concave lower aspect:

a) left bronchus

b) right pulmonary artery

c) ligamentum arteriosum

d) left recurrent laryngeal nerve and

e) superficial cardiac plexus.

Convex upper aspect:

a) brachiocephalic artery

b) left common carotid artery

c) left subclavian artery

d) thymus and

e) left brachiocephalic vein.

1.4. Branches

Three branches arise from the convex aspect of the arch:

- ♥ Brachiocephalic trunk
- ♥ Left common carotid artery
- ♥ Left subclavian artery

They may branch from the beginning of the arch or the upper part of ascending aorta. The distance between these origins varies, the most frequent being approximation of left common carotid artery to the brachiocephalic trunk.[16]

Brachiocephalic artery:

The brachiocephalic (innominate) artery, the largest branch of the aortic arch, is 4-5 cm in length.[16] It arises from the convexity of the arch posterior to the centre of manubrium sterni. It then passes upward and to the right of trachea and divides into right subclavian and right common carotid arteries behind the right sternoclavicular joint.[18]

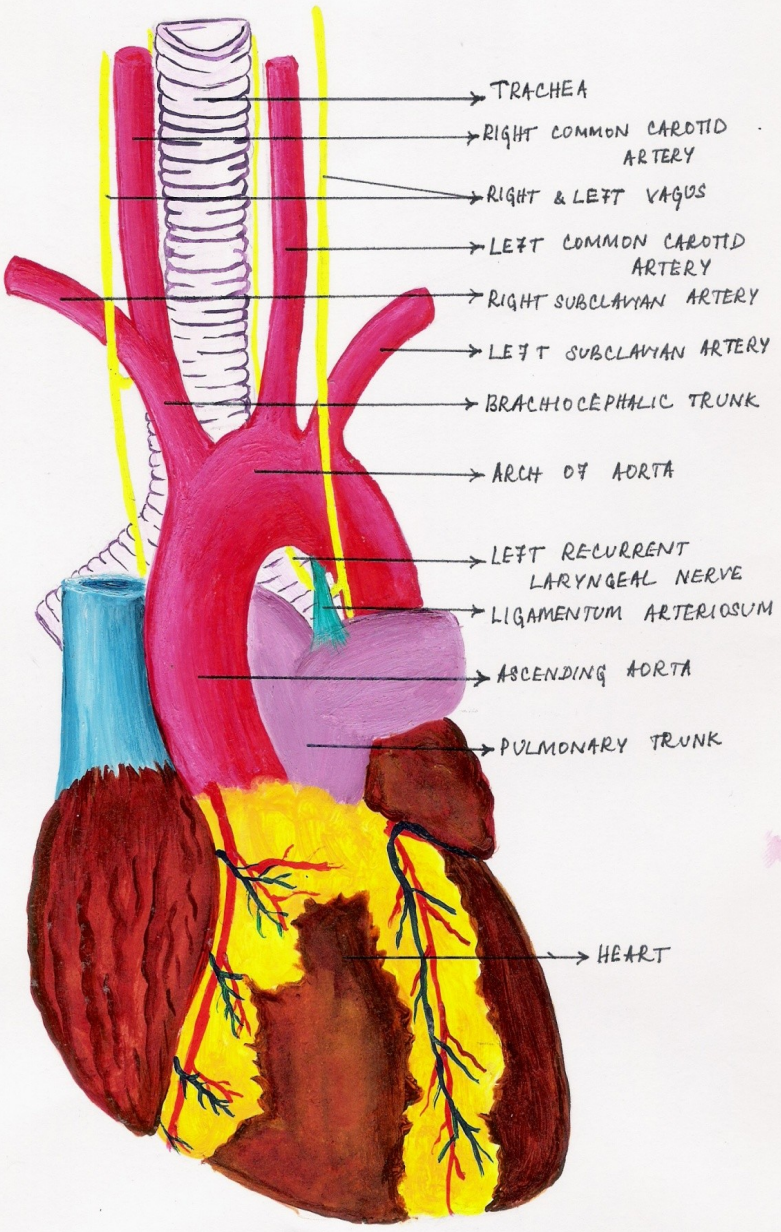

FIGURE 1. NORMAL AORTIC ARCH WITH ITS BRANCHES AND RELATIONS.

Left common carotid artery:

The left common carotid artery (LCCA) originates directly from the aortic arch immediately posterolateral to the brachiocephalic trunk, and ascends until level with the left sternoclavicular joint, where it enters the neck. It is 20-25 mm long[16] and it lies at first in front of the trachea, then it inclines to the left.

Left subclavian artery:

The left subclavian artery (LSCA) arises from the aortic arch below the left common carotid artery and rises into the neck lateral to the medial border of scalenus anterior, crosses behind this muscle and then descends towards the outer border of first rib, where it becomes the axillary artery.[16]

1.5. Dimensions

The diameter of the aortic arch at its origin is 28 mm, but it is reduced to 20 mm at the end,[16] after the issue of its large collateral branches. At the border with the thoracic aorta, a small stricture (aortic isthmus), followed by a dilatation, can be recognized. In foetal life, the isthmus lies between the origin of left subclavian artery and the opening of ductus arteriosus.[16]

1.6. Ligamentum arteriosum (Botallo's ligament)

This is a fibrous remnant of ductus arteriosus (DA). It passes from the commencement of left pulmonary artery to the concavity of aortic arch, beyond the point where the left subclavian artery branches off. It lies almost horizontally. The left recurrent laryngeal nerve hooks around it. The superficial part of cardiac plexus lies anterior to it, and the deep part is on the right, between the aortic arch and tracheal bifurcation.[17]

1.7. Radiographic anatomy

The shadow of the arch is easily identified in anteroposterior radiographs and its left profile is sometimes called the “aortic knuckle”. The arch may also be visible in left anterior oblique views enclosing a pale space, “the aortic window”, in which shadows of the pulmonary trunk and its left branch may be discerned.[16] Computed tomography (CT), magnetic resonance imaging (MRI) and digital subtraction angiography (DSA) can be useful diagnostic tools because they reveal the positions of vascular, tracheobronchial and esophageal structures and their relationships to one another.[19] Gadolinium enhanced three dimensional magnetic resonance angiography, with multi planar reformations and sub volume maximum intensity projection (MIP) is particularly helpful at depicting the origins and courses of the branches of aortic arch.[3]

2. Variations

The aorta may vary in its position and extent without any other irregularities. The height of the arch may be as high as third thoracic vertebra or as low as fifth thoracic. The summit of the arch is usually about 2.5 cm below the superiosternal border.[16] It may reach the top of sternum.[20] It is closer to the upper border of sternum in infants and also in old age, because of dilatation of the vessel.

2.1. Embryology

The first major intraembryonic vessels that develop in the 3-week embryo are the dorsal aortae, which run along the axis of the embryo. As a result of cardiogenic plate rotation and fusion of ventral aortae to form the aortic sac, the

cranial portions of the dorsal aortae become arched and embedded in the mesenchyme of the branchial arches. The paired dorsal aortae fuse to form a midline descending aorta.[21,22]

Six pairs of arteries, called aortic arches, develop from the aortic sac, pass laterally around the developing gut, and connect to the paired dorsal aorta. During the sixth to eighth week of gestation, the six aortic arches along with the seventh segmental dorsal artery from each dorsal aorta develop into the aortic arch and its major branches (Figures 2 and 3).

In human embryos, all aortic arches are never present at the same time. Their formation and remodelling (with the exception of the fifth arch) show a pronounced craniocaudal gradient.[23] The more cranial are in the process of disappearing before the caudal ones are completed. The proximal portion of aortic arch is derived from the left horn of aortic sac and the distal portion is derived from left dorsal aorta. The arch of aorta between left common carotid and left subclavian arteries is derived from the left fourth aortic arch.

The brachiocephalic artery is derived from the right horn of aortic sac. The proximal segment of right subclavian artery is derived from right fourth aortic arch and its distal part from a portion of right dorsal aorta and seventh intersegmental artery. The distal part of left sixth aortic arch persists during intrauterine life as the ductus arteriosus. The proximal parts of the third pair of aortic arches form the common carotid arteries.

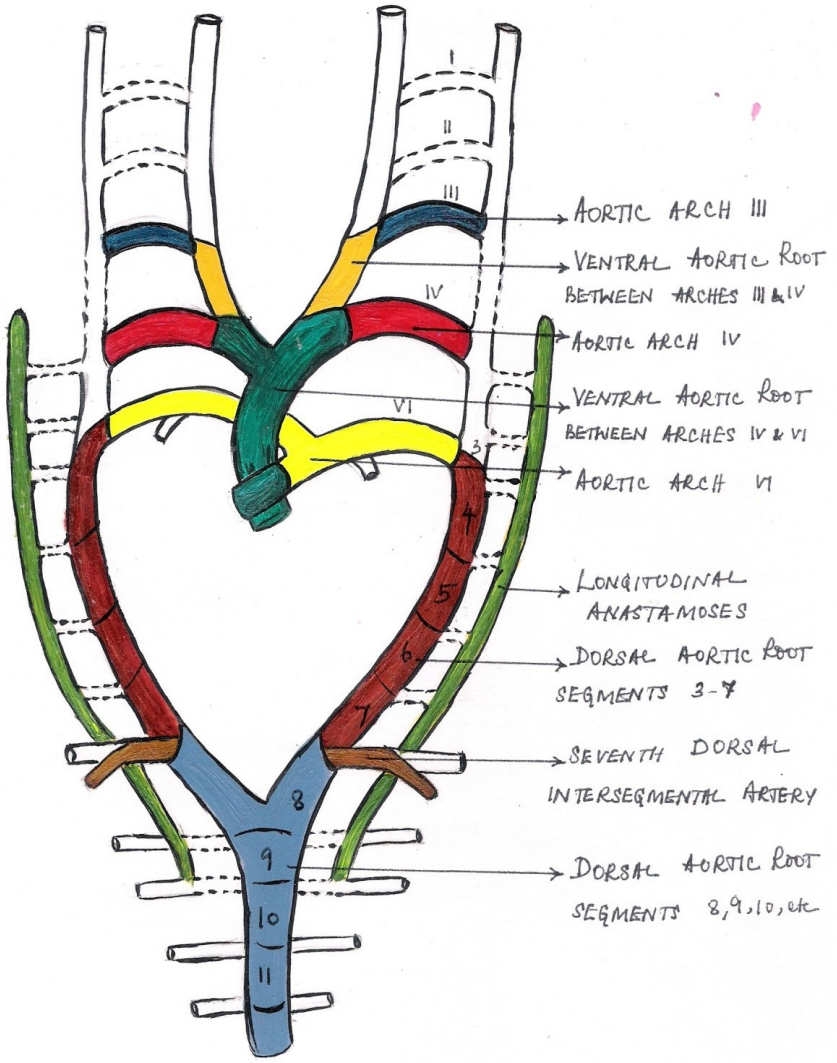

FIGURE 2. COMPONENTS OF THE AORTIC ARCH COMPLEX IN HUMAN EMBRYO.

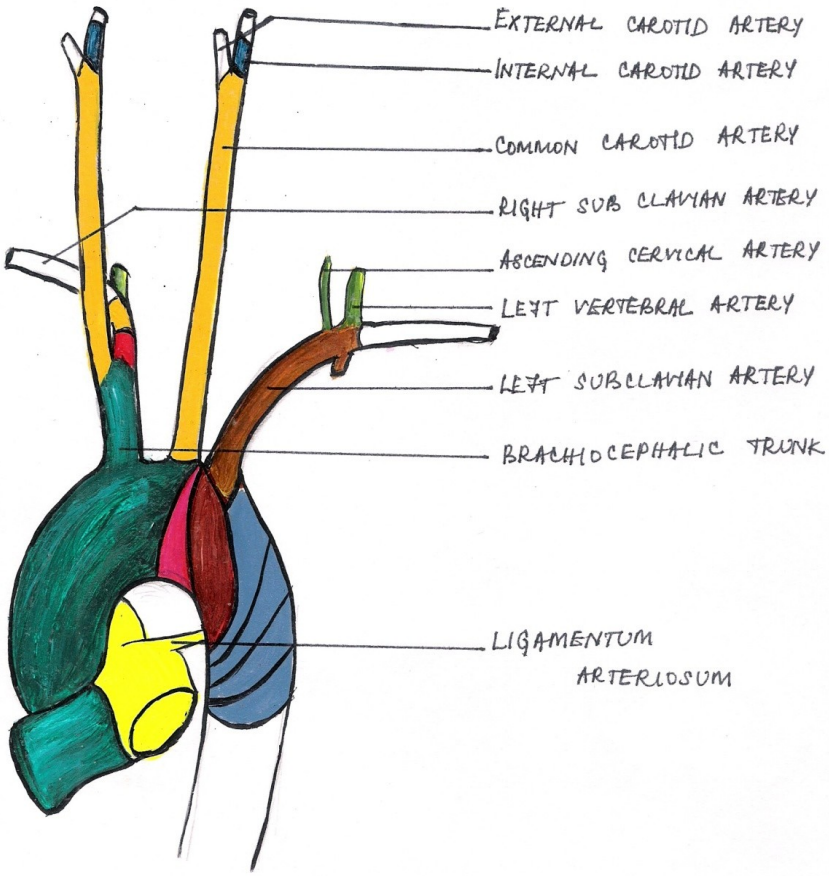

FIGURE 3. ADULT HUMAN AORTA AND ITS BRANCHES SHOWING THE POSITION AND RELATIVE SIZES OF DEFINITIVE CONTRIBUTIONS FROM VARIOUS EMBRYONIC COMPONENTS AS SHOWN IN FIGURE 2.

The left subclavian artery is not derived from an aortic arch but from the left seventh intersegmental artery. As development proceeds, differential growth shifts the origin of left subclavian artery cranially and it comes to lie close to the origin of left common carotid artery. Vertebral artery is formed by the development of longitudinal anastamoses that link the dorsal cervical intersegmental arteries. The intersegmental arteries regress, except for the seventh, which becomes the proximal subclavian artery and which includes the point of origin of vertebral artery in adults.

The transformation of the sixth pair of aortic arches explains why the course of recurrent laryngeal nerves differs on the two sides. These nerves supply the sixth pair of aortic arches on their way to the developing larynx. On the right, because the distal part of the right sixth aortic arch degenerates, the right recurrent laryngeal nerve moves superiorly and hooks around the proximal part of right subclavian artery, a derivative of fourth aortic arch. On the left, the left recurrent laryngeal nerve hooks around the ductus arteriosus formed by the distal part of left sixth aortic arch. When this arterial shunt involutes after birth, the nerve hooks around the ligamentum arteriosum and arch of aorta.[24]

Genomics:

Genetic factors determining aortic arch development and its perturbations are now being elucidated. In 2001, McElhinney *et al*[25] found that chromosome (chr) 22q11 deletion was significantly more common in patients with abnormal branching or laterality of the aortic arch than it was in those with a left sided arch and normal branching of the brachiocephalic vessels.

The internal organs of all vertebrates are symmetrically organised across the left-right axis. The development of this asymmetry is controlled by a molecular pathway that includes the signalling molecule Nodal and the transcription factor Pitx2, proteins encoded by genes that are predominantly expressed on the left side of all vertebrate embryos. At the genome level, cardiac neural crest cells are known to play multiple roles during development of the inflow and outflow tract of the heart and aortic arch. In 2002, Liu *et al*[26] showed that the Pitx2 gene contributes to aortic arch development, suggesting that a major function of the Pitx2 mediated left right asymmetry pathway is to pattern the aortic arches.

2.2. Anomalies of the arch

Recognition of anomalies of the aortic arch date back to 1737, when Homell first described a double aortic arch.[27] In view of the complex events that occur in the development of the aortic arch and its branches, it is not surprising that anomalies occur. When cardiac neural crest is removed from early avian embryos, malformations involving the carotid arteries and arch of aorta result.[23] Most irregularities are the result of persistence of parts of aortic arches that usually disappear, or disappearance of parts that normally persist.[24,28]

A classification of major variations of the aortic arch given by Gross and Ware (1946) and Neuhauser (1946) is as follows[20]:

I. Right aortic arch

A. Situs inversus viscerum

B. Right aortic arch without inversion

1. Anterior type (arch is anterior to the trachea and descending aorta is on the right side)

2. Posterior type (aorta passes to the left behind the esophagus and descending aorta courses to the right)

II. Double aortic arch

A. Both aortic limbs are patent

B. One aortic limb is obliterated

III. Anomalies right subclavian artery

The artery arises last from a normal aortic arch and crosses the midline to its distribution on the right side (behind trachea & esophagus)

IV. Patent ductus arteriosus

V. Coarctation of the aorta (CoA)

Right sided aortic arch

This anomaly reproduces the normal vascular pattern seen in birds.[20,29] A right aortic arch arises from the persistence of the complete embryonic right aortic arch and disappearance in the left arch of the segment caudal to the exit of left subclavian artery. A right aortic arch was first described three centuries ago by Fioratti and Aglietti (1763). Fifty five years later, Corvisart (1818) reported its occurrence in a case of tetralogy of Fallot (Corvisart's disease).[4,5] Liechty, Shields and Anson[30] (1957) found one instance of right sided aortic arch among 1000 cadavers examined.

Right sided aortic arch has been found to be associated with other anomalies such as coarctation of aorta, patent ductus arteriosus, pulmonary stenosis, tricuspid atresia and ventricular septal defect .[5] A right aortic arch with retroesophageal left ligamentum arteriosum was reported by Zhao *et al*[31] in 2006.

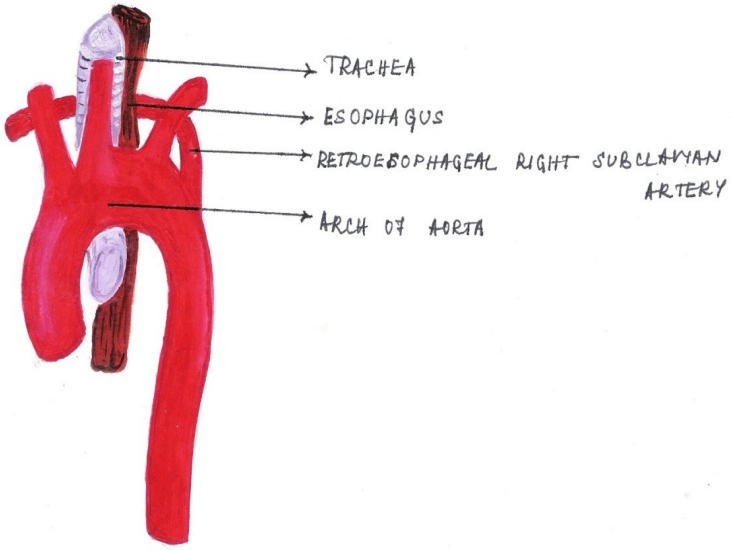

FIGURE 4. ABNORMAL RIGHT SUBCLAVIAN ARTERY ARISING FROM THE AORTIC ARCH, PASSING POSTERIOR TO THE TRACHEA AND ESOPHAGUS AND COMPRESSING THEM.

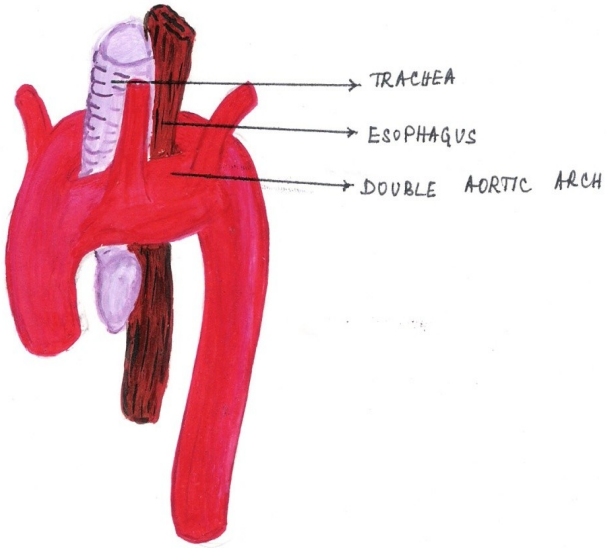

FIGURE 5. DOUBLE AORTIC ARCH FORMING A VASCULAR RING AROUND THE TRACHEA AND ESOPHAGUS.

Double aortic arch

A double aortic arch results when the right dorsal aorta persists between the origin of seventh intersegmental artery and its junction with the left dorsal aorta. This anomaly is characterized by a vascular ring around the trachea and esophagus producing varying degrees of compression of these structures (Figure 5).[21,24]

The right aortic arch is most commonly dominant.[21] The descending aorta is usually in its normal position on the left, as is the ligamentum arteriosum. Generally, each subclavian and common carotid artery arises independently from its respective aortic arch. The brachiocephalic vessels do not develop. 20% of cases have other anomalies, with VSD and ToF being most common.[27] Double aortic arch was first described by Homell in 1737. The first surgical correction of a double aortic arch was performed by Gross in 1945 on a one year old boy with chronic wheezing.[27]

Retroesophageal right subclavian artery

Abnormal origin of right subclavian artery is formed by the distal portion of right dorsal aorta and seventh intersegmental artery. The right fourth aortic arch and the proximal part of right dorsal aorta are obliterated. With shortening of the aorta between left common carotid and left subclavian arteries, the origin of abnormal right subclavian artery finally settles just to the right of left subclavian artery. Since its stem is derived from the right dorsal aorta, it must cross the midline behind the esophagus to reach the right arm (Figure 4).[21]

It is found in about 0.5-1.8% of the population[27] and its incidence is 16 in every 1000 autopsies.[31] Although this anomaly is fairly common and always forms a vascular ring, it is rarely significant clinically, because the ring is usually not

tight enough to constrict the esophagus and trachea.[24] This anomaly is especially associated with three other anomalies – anomaly of right recurrent branch of vagus, right thoracic duct instead of a left one and tracheoesophageal fistula.[32]

Patent ductus arteriosus

Patent ductus arteriosus is one of the most frequently occurring abnormalities of the great vessels, especially in premature infants.[21] Ductus arteriosus is formed from the distal part of left sixth aortic arch. At birth, the ductus constricts, probably as a result of initial exposure of oxygen sensitive muscle cell in its wall to blood with high oxygen content. By one month, the DA is normally obliterated to become ligamentum arteriosum.[28]

Closure of the ductus is not an instantaneous event. Anatomical patency of DA is present in 65% of infants at the age of two weeks and slightly over 1% at the age of one year. The lumen of a patent ductus may vary from a few mm to a size equal to or greater than the aorta. Its length is usually about 1 cm, but may be so short that there is practically an aortopulmonary window, or it may be as long as 3 cm.[6]

Approximately 10% of patients with PDA have associated cardiovascular anomalies. In some of these patients, the presence of a patent ductus serves as a compensatory mechanism to sustain life. In others, the ductus is an isolated anomaly.[6]

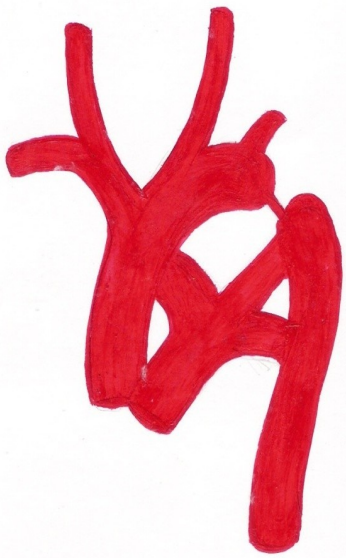

FIGURE 6: COARCTATION OF AORTA.
A - PREDUCTAL TYPE

B - POSTDUCTAL TYPE

Coarctation of aorta

Coarctation (from the Latin “arctare”, to make tight) refers to a congenital or developmental anomaly of the aorta characterized by stenosis or obliteration of a section of that vessel. This malformation was first described by Morgagni in 1760.[1] In 98% of cases, the constriction is at the level of insertion of DA but may be located anywhere between the arch and the bifurcation of aorta.[1] Its incidence according to post-mortem studies is 1:1000[6] and 0.3% in newborn infants.[33] CoA is associated with PDA in 10% of cases.[6]

Two types – preductal and postductal may be distinguished based on the location of the constriction, either above or below the entrance of DA (Figure 6). It results from the incorporation of oxygen sensitive muscle tissue from the DA into the wall of the aorta. Normally, this muscle constricts when exposed to high oxygen tension, closing the DA. If the muscle is also in the wall of the aorta, the aorta constricts at that level. Eventually, chronic changes occur and the constriction becomes permanent.[28]

Absence of aortic arch

It is one of the rare anomalies of aortic arch. Absence of aortic arch means that there is no connection of any kind between the ascending and descending aorta, the latter being the continuation of pulmonary trunk via a PDA. Functionally it corresponds to the most severe form of “infantile type” (preductal) coarctation. It is also called “Steidele’s complex”.[34] Interruption of the aortic arch can occur at any point between the embryonic aortic sac and the ductus arteriosus. Based on the location of the absence of aortic arch, Celorie and Patten have classified this defect into three types – A, B and C. The constant association of this condition with PDA and VSD has led Everts Suarez and

Carson to suggest that these anomalies should be known as a “cardiovascular triology”.[35] This lesion has been produced in mice lacking the winged helix transcription factor MF-1 (mesenchyme fork head-1).[23]

Recurrent laryngeal nerve in variations

The disposition of recurrent laryngeal nerves is normal in cases of CoA and PDA. In cases of posterior subclavian artery, the right recurrent laryngeal nerve is replaced by branches passing directly from vagus to the larynx. In cases of double and right sided aortic arch, it passes around the arch instead of around the right subclavian artery.

The position of left recurrent laryngeal nerve is normal when there is also a left aortic arch or when DA is on the left side, joining the pulmonary artery with a persistent left aortic root. When there is a left brachiocephalic artery and ligamentum arteriosum is on the right side, it winds around the left subclavian artery.[36]

2.3. Anomalies of branching pattern

The most commonly encountered branching pattern in humans consists of three great vessels originating from the arch of aorta, brachiocephalic artery, left common carotid artery and left subclavian artery. The final configuration of the aortic arch and its branches is related to the development of the embryonic aortic arches and the associated migration and merging of their branches.

Many variations occur in the number and position of vessels arising from the aortic arch. More than 15 different aortic arch configurations have been described by Anson (Figure 7).[30]

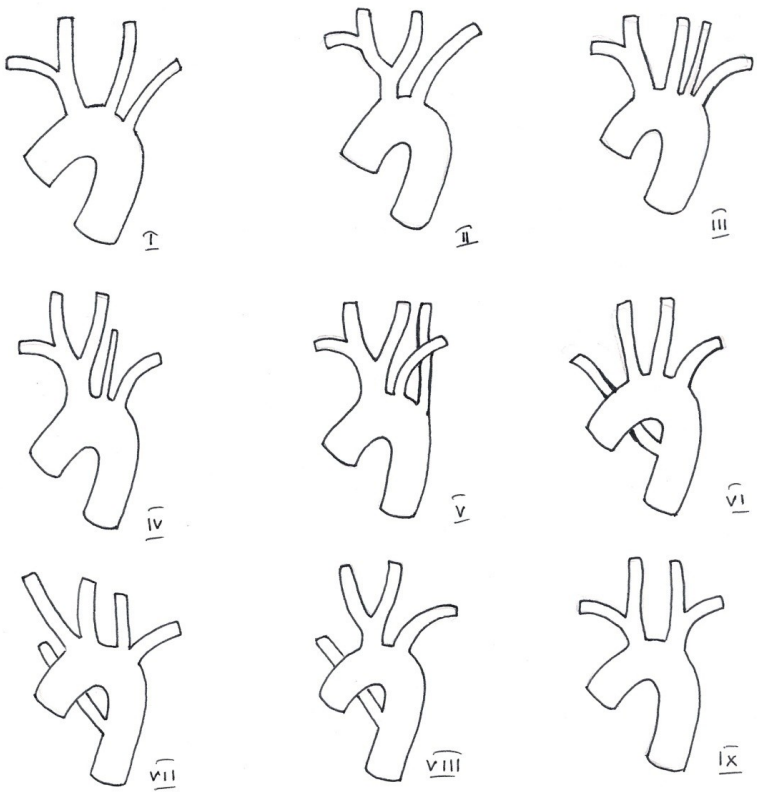

FIGURE 7. TYPES OF BRANCHING OF AORTIC ARCH IN 100 SPECIMENS AS OBSERVED BY ANSON.[30]

I – In this type, three branches leave the arch from right to left in the following succession: innominate, left common carotid and left subclavian.

II – Here both common carotids arise from the innominate reducing the number of branches to two.

III – There is an increase in the number of branches and the additional vessel is left vertebral.

IV – Here the left vertebral artery replaces the left common carotid being second in right to left succession and both common carotids arise from a common stem.

V – The left vertebral artery arises from the innominate, and the order of left common carotid and left subclavian arteries is reversed.

VI to VIII – The right subclavian artery arises as the last branch of aortic arch reaching the right upper extremity by passing dorsal to the esophagus. These types differ with respect to the origin of other vessels.

IX – A bi-innominate sequence in which paired vessels are the only derivatives of the aortic arch.

Cont...

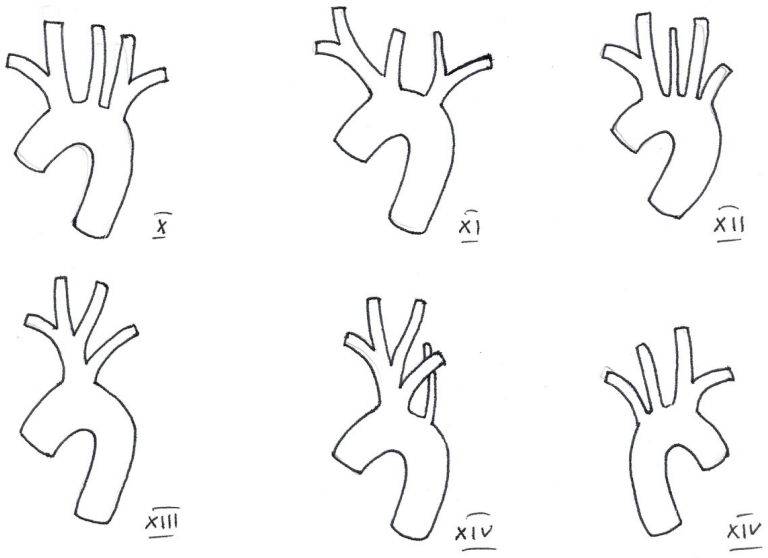

FIGURE 7- CONT. TYPES OF BRANCHING OF AORTIC ARCH IN 100 SPECIMENS AS OBSERVED BY ANSON.[30]

X & XI – In both these varieties the left vertebral artery arises from a common stem from which the left subclavian is also derived. However, in type X a regular innominate artery is present, whereas in type XI, the innominate shares a common trunk with left common carotid.

XII – Here, as in type III, an extra vessel arises from the aortic arch, but the additional vessel being arteria thyroidea ima.

XIII – In this, the usual three branches take origin from the aortic arch through a single trunk as an intermediary vessel.

XIV – Single stem for the usual three branches as in type XIII, with the left vertebral arising as a separate branch from the arch.

XV – A right aortic arch with the branches as a mirror image of the standard scheme of succession.

There may be as few as one or as many as six branches. The common variant in which two vessels arise from the aortic arch is one where the left common carotid artery has a common origin with the brachiocephalic trunk (BCT). A similar but less common variant occurs when the left common carotid artery originates directly from the brachiocephalic artery rather than as a common trunk. Both variants of left common carotid artery have been referred in various textbooks as a bovine type arch, through this term is most commonly ascribed to the common trunk variety.[37] A true bovine arch bears no resemblance to any of the common human aortic arch variations. In cattle, a single great vessel originates from the aortic arch. This large brachiocephalic trunk gives rise to both subclavian arteries and a bicarotid trunk. The bicarotid trunk then bifurcates into right and left common carotid arteries.[38]

A common variant with four vessels, is one in which the left vertebral artery arises directly from the aortic arch between left common carotid and left subclavian arteries. Another variant (1.1%) which differs slightly from the preceding variety is one in which the left vertebral artery replaces the left common carotid artery as the second stem in right to left succession while the left common carotid artery arises as a common trunk with BCT.[30] The anomalies of branches arising from the aortic arch are due to variations in the extent of the fusion process and abnormal absorption of some of the aortic arches in to the aortic sac. Variations in the arterial morphology of aortic arch branches may also be a consequence of alterations in tissue development. Certain growth factors such as placental growth factor, fibroblast growth factor-2, angiopoietins and vascular endothelial growth factor are released by the developing tissues to ensure that they obtain an adequate blood supply. Variation from the normal

pattern of arterial morphology may result from premature or late release of these factors, or increase or decrease in the level of these factors. The vertebral arteries provide blood supply to the posterior neck musculature, rhombencephalon, mesencephalon, occipital lobe and part of temporal lobe of the brain. A direct origin of vertebral artery from the arch of aorta may be a reflection of variation in demand by these structures.[39]

3. Clinical significance

3.1. Historical perspective

In 1789, Bayford wrote a fascinating account of a woman, with a life long history of severe dysphagia, who "fancied that she nourished within her a voracious animal, and attributed all her uneasiness to the fury with which this half starved monster fell upon each morsel in its passage to the stomach". When at the age of 62, "worn out with fatigue and famine she sunk into a grave", he carried out a post-mortem examination and published his delightful description with drawings of an anomalous subclavian artery.[29] Bayford's term 'dysphagia lusoria' (from lusus naturae – freak or prank of nature) is still employed to dysphagia resulting from many vascular anomalies other than an aberrant retroesophageal subclavian artery.[27]

The first successful correction of a congenital cardiac defect was reported by Gross in 1939, when he successfully ligated a PDA.[2] In 1945, it was Gross again who first surgically corrected a double aortic arch.[27] In 1957, DeBakey and colleagues first described aortic arch replacement using ante grade brain perfusion.[40] With the advent of cardiopulmonary bypass, technical problems in

doing aortic arch surgery became considerably simpler. In 1963, Bernard combined deep hypothermia with circulatory arrest and cardiopulmonary bypass for aortic arch operations and dissection. But this became popular only after 1975 when Griepp reported a series of aortic arch replacements using deep hypothermia and circulatory arrest. In 1983, Borst et al reported replacing the aortic arch and leaving a tube graft lying free in the descending aorta, which they called the "elephant trunk technique". In 1990, Crawford, Svensson and colleagues reported replacement of the entire aorta as a planned stage procedure using a modified elephant trunk technique. Currently, aortic arch has become relatively common and safe with a mortality risk of 2% and a stroke risk of 2%.[13] The first video assisted thoracoscopic surgery (VATS) vascular ring division was performed in 1993 at Children's Hospital, Boston, the same institution where Gross had performed the open surgical division 48 years earlier.[13]

3.2. Radiological significance

Congenital anomalies of the aortic arch and its branches produce recognizable effects largely through distortion of esophagus and trachea. Diagnosis could hardly progress until radiology contributed its essential quota. The studies of Evans (1936) on the esophagus, and of Fray (1936) and of Bedford and Parkinson (1936) on right sided aorta, laid the foundations of radiological diagnosis, now advanced to a high degree of precision. The nature of many of the anomalies of aortic arch in radiographs may be determined by characteristic combination of great vessel shadows, lateral deviations of trachea and esophagus, rounded pressure defects in the contour of trachea and rounded or oblique defects in the contour of esophagus.[41]

Most of the anomalies of the aortic arch are usually asymptomatic. Therefore, radiographic demonstration of such abnormalities is often a first indication of their existence.[42] Chest radiography is the first and most commonly performed investigation. Many authorities consider barium esophagography to be the most important study in patients with suspected vascular ring and it is diagnostic in the vast majority of cases.[19] CT can make apparent the size and orientation of the aortic arch and determine the origin and course of aberrant subclavian arteries.[42]

Multi detector CT (MDCT) can also provide exquisite images, but is rarely used because of its radiation implications. Angiography, previously the imaging procedure of choice, is now rarely required unless cardiac catheterization is necessary for the investigation of associated cardiac abnormalities.[19] Gadolinium enhanced three dimensional angiography with multi planar reformations and sub volume MIP is particularly helpful at depicting the origins and courses of branch vessels.[3] High resolution multi detector row CT angiography enables the display of images from different views. These can be useful as a roadmap in interventional and surgical and therapeutic decision making, especially in patients with complex aortic arch anatomy.[43]

Foetal sonographic diagnosis of aortic arch anomalies

Recognition of trachea, three vessels branching from the aortic arch, ductus arteriosus and descending aorta in the axial views of the upper mediastinum is necessary for a complete foetal cardiac assessment. Clues to aortic arch anomalies include abnormal position of the descending aorta, absence of the normal 'V' shaped confluence of ductal and aortic arches, a gap

between the ascending aorta and main pulmonary artery in the three vessel view and an abnormal vessel behind the trachea with or without a vascular ring or loop around the trachea. Meticulous attention to anatomical landmarks will lead to successful prenatal diagnosis of important vascular rings, making early postnatal management possible.[44]

3.3. Surgical significance

Knowledge of variations of great vessels like the aortic arch and its branches is of vital interest to surgeons because even a minor accidental injury of the vessels may cause sudden massive haemorrhage, shock & fatalities in the operation theatre.[45]

Percutaneous carotid revascularisation is used with increasing frequency to treat carotid atherosclerotic disease. Classically the procedure is performed from the femoral approach, with a long sheath placed into the common carotid artery, and angioplasty and stenting performed through this. Congenital anomalies of the aortic arch increase the technical difficulty of this procedure. In 2003, Shaw *et al* [10] reported three cases of bovine arch associated with increase in the level of case difficulty when performing left carotid stenting from the femoral approach. According to them, the right upper extremity (radial or brachial) approach is preferable when there is a left carotid target lesion in the presence of a bovine arch.

In the study conducted by Fagolli GL[9] in 2007, it was concluded that bovine arch was associated with increased failure and neurological complication rate in carotid stenting procedures. Therefore, the presence of an aortic arch anomaly should caution the vascular surgeon to avoid strenuous attempts to

accomplish such stenting procedures and in the presence of arch anomalies, stenting should be reserved for patients with high surgical risk.

Retroesophageal right subclavian artery is important to the angiographer who uses the right axillary, brachial or radial approach to the ascending thoracic aorta. The presence of the anomaly is suspected in cases in which catheterization of the ascending aorta proves difficult.[46]

The usual clamping techniques used in surgical aneurysms of the aortic arch could not be performed in cases where the left common carotid artery arose from the brachiocephalic artery. In such cases, it is necessary to implement total circulatory arrest in order to repair the aneurysm completely.[47]

According to Bernardi and Detori (1975),[49] the abnormal origin of vertebral arteries "may favour cerebral disorders because of alterations in cerebral hemodynamics".[48] In 2005, Dudich *et al*[49] postulated that anomalous vertebral artery origin may be an independent risk factor for arterial dissection; the longer extra cranial course may lead to increased vulnerability of the vessel wall to shear stress resulting in intimal tear and dissection.

Komiyama *et al*[11] in 2007 retrospectively examined the angiograms of 1109 patients to evaluate arterial dissection of intracranial or extracranial vertebral arteries and the origin of vertebral artery from the aorta or subclavian artery. They concluded that left vertebral artery of aortic origin is associated with a predilection for vertebral artery dissection in comparison to left vertebral artery of subclavian artery origin. Shear stress may be larger in the vertebral artery of aortic origin than in the vertebral artery of subclavian artery origin, possibly due to anatomical differences. The vertebral artery of aortic origin may receive direct

pulsatile flow whereas vertebral artery of subclavian artery origin may receive damped flow due to the presence of the proximal subclavian artery.

The true value of detecting anomalous origins is the diagnostic gain prior to the surgery of supra aortic arteries. Detailed knowledge of an anomalous origin of supraaortic arteries is also important in patients who have to undergo four vessel angiography in an emergency to rule out the possibility of intracranial aneurysm after subarachnoid haemorrhage. If the detection of a vertebral artery in the normal position is not possible, the presence of a variant of vertebral artery arising from the aortic arch must be taken into consideration.[50]

Anatomy of the vertebral artery and its variations is critical for surgeons to help avoid serious complications during surgery in the brain, neck and chest regions.[51] Anomalous vertebral artery might constitute a risk factor for the development of a saccular aneurysm at the origin of a posterior communicating artery, with increased hemodynamic risk or vertebrobasilar insufficiency.[52]

In 2006, Kahraman *et al*[53] measured the diameters of the various branches of the aortic arch in patients with coronary artery ectasia and compared them to a control group. They concluded that in the coronary artery ectasia group, the diameters of all arteries arising from the aortic arch were significantly larger than the corresponding arteries in the control group.

Occlusive disease of branches of the aortic arch

That obstruction of arteries at the point of origin from the aortic arch can cause circulatory disturbances in the head or arms has long since been recognized, having been described by Broadbent in 1875[8] and Penzoldt in

1881.[40] In Japan in 1908, Takayasu[54] first reported a syndrome characterized by loss of pulsations in the radial arteries, absence of detectable blood pressure in the arms, syncope and visual disturbances. Caccamise and Whitman are accredited with reporting the first authentic case in the US (1952) and called the syndrome "pulseless disease".[54] Pulseless disease is also known as anisophygmia, pulsus incongruens or pulsus differens and Takayasu's disease. The syndrome caused by obstruction of the branches of aortic arch was called "the aortic arch syndrome" by Ross and McKusick in 1953.[55] Anomalous aortic arches might contribute to vascular occlusion in aneurysm of aorta. Martorell and Fabre in 1944 and again in 1954 best described this syndrome of occlusion of the supra aortic branches, which has been frequently referred to as "Martorell syndrome".[54]

II. Casting

1. History

The earliest example of casts being made of an anatomical cavity are those of cerebral ventricles by Leonardo da Vinci (1452-1519). He used molten wax for his work, but as he had no method of hardening the brain before making the injection, the casts obtained bore little resemblance to the actual cavities. The introduction by Jan Swammerdam (1637-1680) of molten wax injection masses for filling arteries, veins and ducts, pointed the way to the preparation of corrosion casts, in which, the original tissues are corroded away by means of some reagent which does not attack the cast. But casts made of wax were very fragile. The next substance to be used for this work was a low melting point metal alloy,

with which Govert Bidloo (1649-1713) succeeded in making casts of the bronchial tree.[56] The technique was refined and popularised by Swammerdam's student Ruysch, during the following fifty years, but the interest in vascular casting was greatly diminished by the middle of the 18th century. Hyrth in 1873 published a most elegant monograph in corrosive preparations. His illustrations clearly demonstrate injections of minute macroscopic blood vessels.[57]

2. Methods

A notable advance in the technique for the preparation of corrosion casts was made when Paul Schiefferdecker in 1882 described a method using celloidin (cellulose nitrate) dissolved in ether. Celloidin casts have to be kept in fluid as when celloidin becomes dry it crumbles. In 1899, Carl Storch substituted celluloid (cellulose acetate) for celloidin, so that it was no longer essential to preserve the casts in fluid. In 1903, Mme.Krasuskaja recommended the substitution of acetone for ether as the solvent. In 1936 Narat and others described the use of a vinyl resin dissolved in acetone, as a substitute for cellulose acetate. The appearance in 1948 of cold setting synthetic unsaturated polyester resins opened up new possibilities in the sphere of anatomical casting. They make it possible to produce beautiful, rigid, coloured casts of any large anatomical cavity. But the extent of the injection is impossible to control while using synthetic resins.[56]

With the advent of modern chemistry, elastic materials like latex came into use, and more recently, different materials like silicon rubber, polyester or acrylic resins were introduced.[58,59] According to requirements, coloured or radio opaque materials were added.[60] Measurement of the casted structures with silicon showed a close correlation with those obtained by echocardiography.[59] Burskirk

EMV used Batson's methylmethacrylate corrosion compound no. 7 for his specimens.[61] Live casting of the vascular tree of an animal using silicon was performed by Sobin SS in 1965 and Xue Mei Li in 2003.[57,62]

Gaillord P *et al*[63] embedded wax copies of methyl methacrylate corrosion casts of cervicocranial arteries with liquid silicon modified into transparent blocks. These blocks after wax evacuation, contained hollow reproductions of the original vascular trees. The models were connected to a pulsatile pump and their compatibility with various imaging techniques and endovascular treatment materials was evaluated. The models were compatible with DSA, CT, MRI and transcranial Doppler sonography. They provided a realistic endovascular environment for the simulation of interventional stent procedures.

3. Advantages

The in vitro vascular models are easy to handle, respect human morphological characteristics and are fairly reproducible. They have been shown to provide realistic experimental settings for hemodynamic studies and may also represent an interesting alternative to animal models for the evaluation of endovascular treatment methods, with the exception of biocompatibility studies.[63]

The resilience and non adhesiveness of the silicon rubber allowed casts to be extracted without recourse to corrosion. The surrounding tissues were then available for conventional pathological examinations. Thus, silicon casting is a relatively a simple technique with important applications, not practicable using earlier casting materials for the study of vascular morphology and for the post mortem evaluation of stenosed, malformed or surgically reconstructed vessels.[64]

Materials and Methods

Design

Comparative study.

Time of the study

The study was conducted from August 2006 to June 2008.

Setting

Dissection laboratory of the Department of Anatomy, Thanjavur Medical College and autopsy room of the Department of Forensic Medicine, Thanjavur Medical College.

Inclusion criteria

Specimens from adult human cadavers aged more than 20 years of both sexes in the Department of Anatomy and from autopsied cadavers in the Department of Forensic Medicine during the period August 2006 to June 2008 were included in the study.

Exclusion criteria

Specimens from cadavers aged less than 20 years.

Parameters studied

- Position of the aortic arch in relation to oesophagus:
  - right / left
  - anterior / posterior

- Number of branches arising directly from the arch of aorta
- Anomalies present
- Diameters of the human aortic arch and its branches at various levels (Figure 8)
- Taper ratio

Sample size

100.

Statistical analysis

Data were entered in Microsoft Excel spread sheets. One way ANOVA with Tukey's post hoc test was used for comparison between groups. Repeated measures ANOVA was used to analyse the parameters measured at various levels in the same specimen. This was done using GraphPad Instat version 3.01 for Windows (GraphPad Software, San Diego, California, USA). $P<0.05$ was considered statistically significant.

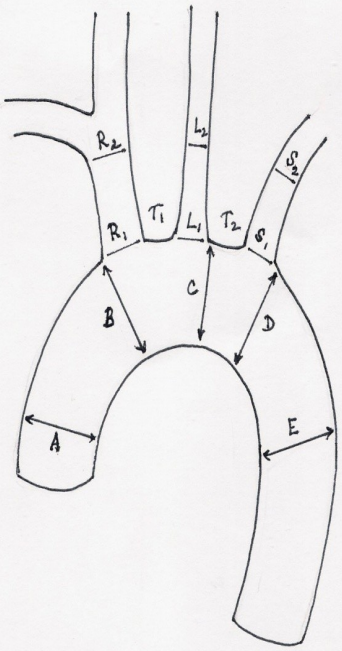

FIGURE 8. DIAGRAM OF AORTIC ARCH AND ITS BRANCHES SHOWING THE SITES AT WHICH MEASUREMENTS ARE MADE.

A – ascending aorta 25 mm proximal to the origin of brachiocephalic artery.

B – proximal to the origin of brachiocephalic artery.

C – distal to the origin of brachiocephalic artery.

D – distal to the origin of left subclavian artery.

E – descending aorta 25 mm distal to the origin of left subclavian artery.

R1 – origin of brachiocephalic trunk.

R2 – 15 mm distal to R1.

L1 – origin of left common carotid artery.

L2 – 15 mm distal to L1.

S1 – origin of left subclavian artery.

S2 – 15 mm distal to S1.

T1 – distance between adjacent margins of R1 and L1.

T2 – distance between adjacent margins of L1 and S1.

Procedure

The heart with the aortic arch and its branches were removed en bloc from cadavers in the Department of Anatomy, Thanjavur Medical College and at autopsy in the Department of Forensic Medicine, Thanjavur Medical College from 100 adult human cadavers in the age group of 20 – 70 years, during the study period.

The specimen was removed from the cadaver as described in Cunningham's manual of practical anatomy - an incision was made in the skin

from the mentum to the xiphisternum and the skin was reflected. Transverse cut was made through the manubrium sterni immediately inferior to its junction with the first costal cartilage. Then the second and subsequent ribs and intercostals spaces were cut inferiorly, to the level of xiphisternal joint. The inferior part of the sternum was gently elevated and the pleura was cut to expose the lungs. The root of the lungs were cut from above downwards after pulling the lungs laterally from the mediastinum, and removed. A cut was made over the middle of each clavicle and the first rib and the manubrium sterni was turned upwards. The veins were then displaced to expose the aortic arch and its branches. The diaphragm was cut around the inferior margin of the heart and the branches of the aortic arch along with trachea and oesophagus were cut as high as possible in the neck.

The heart with the aortic arch and its branches thus removed were washed thoroughly in running water and preserved in a solution containing 10% formalin and thymol after serially numbering them from 1 – 100. The specimen were then dissected and studied with regard to any anatomical variations in their branching pattern. The diameters of the aorta and its branches were determined at various levels and metric analysis was performed by use of a movable calliper with 0.05 mm of possible error. All values were expressed as mean ± SEM.

Photograph 1. Vernier calliper for measuring arterial diameter.

From the values obtained for the diameter of the aortic arch, taper ratio was calculated by using the formula,[12]

Calculated taper ratio was analysed for statistical significance between the three groups.

Confirmation

In specimens sharing a common trunk for the brachiocephalic and left common carotid artery, the presence of the common ostium was confirmed either by direct examination of the ostium on its luminal side by making a slit on the posterior surface of the aortic arch or by making luminal silicon casts of those specimens.

Luminal casting

The specimen was washed thoroughly in running water and flushed with spirit to remove blood and secretions and allowed to air dry. General purpose silicon gel tube (Wacker) was fitted onto a metallic gun designed for this

purpose and its canula was introduced into the descending thoracic aorta with its tip towards the aortic arch. The cut ends of the branches of the aortic arch and the pulmonary vessels were tightly secured with silk.

Now silicon was injected retrograde into the aorta. The injection was stopped when the aorta and all its branches were filled up with silicon. The canunla was removed and the free end of the descending thoracic aorta was ligated. It was allowed to cure for 24 hours. The surrounding tissues were then removed from the cast by careful dissection to reveal an anatomical replica that illustrates clearly the common origin of brachiocephalic and common carotid arteries.

Photograph 2. Luminal casting gun with general purpose silicon gel.

Results

Hundred aortic arches were dissected and studied with respect to the branches arising from them and the specimens were divided into various types based on Anson's classification[32] (Table 1). In the present study, five types of branching pattern were observed.

- Type I – aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order (Photographs 3 and 4).
- Type II – common trunk for BCT and LCCA (Photographs 5 and 6).
- Type III – left vertebral artery as an additional branch from the arch in between the origins of LCCA and LSCA (Photograph 7).
- Type IV – coexistence of Type II and Type III anomalies (Photograph 8).
- Type IX – left brachiocephalic trunk from the arch dividing into LCCA and LSCA (Photograph 9).

Table 1. Classification of branching pattern of aortic arch in 100 cadaveric specimens.

Type of Anomaly*	No. of branches	Frequency(%)	Specimen no.
I	3	79	2,3,5,8,10,11,.....
II	2	14	1,4,6,7,13,32,.....
III	4	4	9,57,59,67
IV	3	2	18,61
IX	2	1	34

*Based on Anson's classification. Type I – aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order; Type II – common trunk for BCT and LCCA; Type III – left vertebral artery as an additional branch from the arch in between the origins of LCCA and LSCA; Type

IV – coexistence of Type II and Type III anomalies; Type IX – left brachiocephalic trunk from the arch dividing into LCCA and LSCA.

Photograph 3. Aortic arch in situ with normal branching pattern (Type I).

Photograph 4. Aortic arch with normal branching pattern (Type I).

Photograph 5. Aortic arch with common stem for brachiocephalic and left common carotid arteries (Type II).

A. B.

Photograph 6. Luminal casting of Type II branching pattern of aortic arch.

A. B.

Photograph 7. Left vertebral artery arising from the aortic arch between left common carotid and left subclavian arteries (Type III).

A. B.

C. D.

Photograph 8. Coexistence of Type II and Type III anomalies in the same specimen (Type IV).

A. B.

Photograph 9. Aortic arch with common stem for left common carotid and left subclavian arteries (Type IX). A. Anterior view B. Posterior view showing the window made for confirming the common ostium.

A. B.

The relative proportions of the various types of aortic arch branching is depicted in the following pie chart (Figure 9).

Figure 9. Frequency of types* of aortic arch branching pattern in 100 human adult cadavers.

*Based on Anson's classification. Type I – aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order; Type II – common trunk for BCT and LCCA; Type III – left vertebral artery as an additional branch from the arch in between the origins of LCCA and LSCA; Type IV – coexistence of Type II and Type III anomalies; Type IX – left brachiocephalic trunk from the arch dividing into LCCA and LSCA.

Dimensions of the aortic arch and its branches were measured at various levels. For purpose of comparison of these dimensions, the specimens were divided into three groups (Table 2).

- The first group includes Type I aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order. Since this type occurs more frequently, it is designated as normal in this study.

- The second group includes those specimens in which the brachiocephalic and left common carotid arteries share a common trunk of origin. Also included in this group are two specimens in which the common trunk was present in addition to the anomalous aortic origin of left vertebral artery. Because there is only one instance where the left common carotid and left subclavian artery share a common left brachiocephalic trunk, this specimen was also included in the common trunk category.

- The third group includes specimens in which aortic origin of left vertebral artery existed as an isolated anomaly or along with a common trunk for the brachiocephalic and left common carotid arteries.

Table 2. Grouping of anomalies of branching pattern of arch of aorta in 100 cadaveric specimens.

Group	No. of specimen n=100*	Specimen No.
I – Normal	79	2,3,5,8,10,11,.....
II – Common trunk	17	1,4,6,7,13,18,32,34,.....
III – Aortic left vertebral artery	6	9,18,57,59,61,69

Total number of specimens does not add to 100 as two specimens have both anomalies. Group I – aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order; Group II – common trunk for BCT and LCCA; coexistence of the common trunk variety with aortic origin of left vertebral artery; left brachiocephalic trunk from the arch dividing into LCCA and LSCA; Group III – left vertebral artery as an additional branch from the arch in between the origins of LCCA and LSCA.

The dimensions of the three branches of aortic arch (at their origin from the arch and 1.5 mm away from the origin) and the distances between them were measured and their mean values in the three groups calculated (Table 3).

Table 3. Dimensions of the branches of aortic arch and the distance between its three branches.

Parameter (mm)	Normal n=79	Common trunk n=17	Aortic left vertebral artery n=6
R1	9.5 ± 0.2	10.4 ± 0.5	11.3 ± 1.0*
R2	8.5 ± 0.2	8.5 ± 0.5	9.8 ± 0.8
L1	6.6 ± 0.1	7.4 ± 0.3	7.5 ± 0.3
L2	5.6 ± 0.1	6.2 ± 0.3	6.8 ± 0.3*
S1	7.7 ± 0.2	7.5 ± 0.5	8.2 ± 0.9
S2	6.5 ± 0.2	6.1 ± 0.3	6.8 ± 0.7
T1	5.0 ± 0.2	-	5.8 ± 1.1
T2	7.2 ± 0.2	7.9 ± 1.1	11.8 ± 1.3

Values are mean ± SEM.*P < 0.05, compared to normal by one way ANOVA followed by Tukey's post hoc test. R1 – origin of BCT, R2 – 15 mm distal to R1, L1 – origin of LCCA, L2 – 15 mm distal to L1, S1 – origin of LSCA, S2 – 15 mm distal to S1, T1 – distance between adjacent margins of R1 and L1, T2 – distance between adjacent margins of L1 and S1.

The diameters of the aortic arch at multiple sites in the three groups from its origin to its termination were estimated and variations in diameter of aortic arch as its branches are given off were compared within groups (Table 4).

Table 4. Diameters of the aortic arch (mm) at multiple levels in the three groups.

Group	A	B	C	D	E
Normal (n=79)	20.4±0.3	19.9±0.3	17.9±0.9	16.6±0.3	15.7±0.3
Common trunk (n=17)	18.8±0.6*	18.6±0.5	16.6±0.5*	15.9±0.6*	15.3±0.6
Aortic left vertebral artery (n=6)	20.5±1.0*	20.3±0.8	18.3±1.0*	17.3±1.2*	15.8±1.5

Values are mean ± SEM. A – ascending aorta 25 mm proximal to the origin of BCT, B – proximal to the origin of BCT, C – distal to the origin of BCT, D – distal to the origin of LSCA, E – descending aorta 25 mm distal to the origin of LSCA. Total number of specimens does not add to 100 as two specimens have both anomalies.

Figure 10. Diameter of aortic arch at different levels.

Values are mean ± SEM. $p>0.05$, when diameters were compared between groups by one way ANOVA followed by Tukey's post hoc test. A – ascending aorta 25 mm proximal to the origin of BCT, B – proximal to the origin of BCT, C – distal to the origin of BCT, D – distal to the origin of LSCA, E – descending aorta 25 mm distal to the origin of LSCA.

Figure 10 illustrates the trend of decreasing diameter of aortic arch from its proximal to distal level in the three groups. The mean taper ratio calculated from the diameter at the proximal and distal end of the aortic arch was 22.57 ± 0.67%. The taper ratio of the three groups was 23.11 ± 0.77% (Group I),

18.88 ± 1.3% (Group II) and 23.4 ± 3.4% (Group III) and they do not differ significantly (Figure 11).

Figure 11. Taper ratio of aortic arch.

Values are mean ± SEM. p>0.05, considered not significant. Group I – aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order; Group II – common trunk for BCT and LCCA; coexistence of the common trunk variety with aortic origin of left vertebral artery; left brachiocephalic trunk from the arch dividing into LCCA and LSCA; Group III – left vertebral artery as an additional branch from the arch in between the origins of LCCA and LSCA.

Discussion

In the present study conducted on cadaveric specimens, the branching pattern of the aortic arch described as normal (Type I) was observed in 79 of the 100 specimens. The most common anomaly was the presence of a common stem for the brachiocephalic and left common carotid arteries (Type II) which was observed in 14% of the specimens. The next common anomaly was observed in 4% of specimens, in which the left vertebral artery arose directly from the aortic arch in between the origins of left common carotid and left subclavian arteries (Type III). In two of the specimens both the above mentioned anomalies co-existed (Type IV). And one specimen had a common stem for the left common carotid and left subclavian arteries (Type IX). The frequency of the various types of the branching pattern of the aortic arch in previous studies and the present study is given in table 5.

Type II

The most common anomaly in our study is Type II. This is the type of branching found in most apes.[20]

Preservation of distal blood flow and cerebral protection are of major concern during surgical repair of aneurysms of the brachiocephalic trunk, where the aorta is sequentially or partially clamped. If the left common carotid artery arose as a common stem with the brachiocephalic trunk such clamping techniques could not be used and in order to repair the aneurysm completely total circulatory arrest has to be implemented.[47]

Classically, percutaneous carotid angioplasty and stenting is performed from the femoral approach with a long sheath placed into the common carotid artery. In 2003, Shaw JA[10] observed that stenting could not be performed in the usual manner in Type II anomalies and carried out the technique with some modifications. In one case, because of angular take off of left common carotid artery, a 7 Fr shuttle sheath could not be advanced into the common carotid and a more flexible 6 Fr was substituted. In another case, despite attempts with various catheters from the femoral approach, adequate access to the common carotid could not be achieved. Hence, a radial approach was chosen and stenting procedure was performed successfully.[10]

From the above two studies it becomes clear that Type II anomaly plays a pivotal role in deciding the choice of approach to stenting and the necessity of total circulatory arrest in aortic aneurysm repair. Therefore the presence of such an anomaly must be confirmed before any surgery on the aortic arch is attempted.

Type III

The next most common pattern is one in which the left vertebral artery arose as a direct branch from the aortic arch (Type III). This is observed in 6% of the specimens. Dissecting aneurysms of the left vertebral artery is more common when it arose directly from the aortic arch than when it arose from the subclavian artery.[11] Two possible mechanisms have been postulated for this :

i) vertebral artery of aortic origin may receive direct arterial pulsatile flow whereas vertebral artery of subclavian origin may receive damped flow due to the presence of the proximal subclavian artery;

ii) the longer extracranial course may lead to increased vulnerability of the vessel wall to shear stress resulting in intimal tear and dissection.[11]

Table 5. Frequency (%) of various types of branching of aortic arch as reported in scientific literature.

S.No	Author	Year	Type I	Type II	Type III	Type IV	Type IX
1	Thompson[65] (n=500)	1893	82.4	10.2	5.4	0.4	-
2	Adachi [65] (n=516)	1928	83.3	10.9	4.3	0.6	-
3	William JD[65] Negro(n=79) White(n=80)	1932	 53.7 75.0	 42.4 19.4	 2.8	 - -	 - -
4	William JD[66] Negro(n=137) White(n=111)	1935	 56.9 75.9	 37.0 17.8	 2.0 2.6	 1.8 0.5	 - -
5	Anson[32] (n=1000)	1957	64.9	27.1	2.5	1.1	-
6	Wright NL[67] (n=100)	1969	85	7	8	-	-
7	Gupta[68] (n=100)	2005	77	7	7	3	2
8	Present study (n=100)	2008	79	14	4	2	1

Type I – aortic arch with three branches – brachiocephalic, left common carotid and left subclavian arteries in that order; Type II – common trunk for BCT and LCCA; Type III – left vertebral artery as an additional branch from the arch in between the origins of LCCA and LSCA; Type IV – coexistence of Type II and Type III anomalies; Type IX – left brachiocephalic trunk from the arch dividing into LCCA and LSCA.

Anomalous vertebral artery origin also represents a potential pitfall in diagnostic cerebrovascular imaging. It may be wrongly assumed to be occluded or diseased either by eluding catheterization during angiography or by lying outside the region of interest during non invasive studies such as CT

angiography, MR angiography or Doppler sonography.[52] A variant of the subclavian steal syndrome can occur when proximal stenosis of the subclavian artery is combined with a vertebral artery of aortic origin. Brain ischemia is known to occur in such cases particularly with ipsilateral limb exercise, as the extra blood supply to the upper limb on the affected side is maintained at the expense of blood flow to the brain via vertebral artery.[39]

It is to be noted here that some types of variation in the aortic arch and its branches encountered as surgical problems, did not occur among the dissection room specimens. This is an expected circumstance, since these atypical patterns are likely to be associated with compression of the esophagus or trachea or with tetralogy of Fallot. The former condition if left untreated results in early death. Similarly life expectancy in untreated cases of the latter sort is poor.[30]

Aortic dimensions:

The diameter of the aortic arch shows a decreasing trend from its proximal to distal portion. This decrease is evident in all three groups (Figure10). The quantity of blood reaching the distal end of the arch is much reduced as all branches of the arch are given off proximal to this level. In order to maintain the pressure in the aorta inspite of this reduced blood flow, the diameter also decreases. This correlates with similar studies conducted by Xu SD[12] and Meurs HV.[70] This tapering of the aorta from its proximal to distal end assumes great importance in designing stent-grafts used in endovascular repair of aortic dissection. Most currently available commercial stent-grafts used in the treatment of aortic dissection do not have a tapered design. Xu *et al*[12] reported a case

where the descending aorta showed excessive dilatation six months after stent-graft implantation. In another case, the dissected membrane was ruptured by the distal end of the stent-graft immediately after deployment because of excessive radial force. Then they used specially ordered stent-grafts with a tapered design (taper ratio of 15%),[12] and observed no obvious dilatation of the descending aorta even after one year.[12] The mean taper ratio obtained in this study is 22.57 ± 0.67% and the taper ratio did not differ significantly between the three groups (Figure 11).

The left subclavian artery is an appreciably larger vessel than the left common carotid artery as evident from the measurement of their diameters at their origins and 15mm from their origin (Table 3). This might seem contradictory in view of the vital distribution of the common carotid, but not if one considers the large number of branches the left subclavian is required to feed.

The diameter of brachiocephalic trunk at its origin and that of left common carotid artery 1.5 cm distal to its origin is significantly larger ($p<0.05$) in specimens in which the left vertebral artery arose directly from the aortic arch than when it arose from the left subclavian artery. The diameter of the branches of the aortic arch at other sites did not differ significantly among the three groups.

Table 6. Comparison of diameter (mm) of the aortic arch at different points in various studies.

Author	A	B	C	D	E
Wright NL[67] (n=100)	24.5±0.76	23.0±1.37	20.5±4.06	19.5±2.53	19.0±1.14
Hager[70] (n=70)	30.9±4.1	29.4±4.2	27.7±3.7	26.1±4.1	24.7±4.0

Present study* (n=100)	20.14±2.84	19.69±2.72	17.69±2.74	16.49±2.63	15.57±2.48

Values are mean ± SD. *All the values of the present study are statistically significant ($p<0.001$) when compared to the values of Wright and Hager. A – ascending aorta 25 mm proximal to the origin of BCT, B – proximal to the origin of BCT, C – distal to the origin of BCT, D – distal to the origin of LSCA, E – descending aorta 25 mm distal to the origin of LSCA.

The diameter of the aortic arch at different points (A to E) in our study differ significantly ($p<0.001$) from the values measured by Wright NL[67] and Hager[70] (Table 6). This might be due to the fact that Hager has measured the diameters by CT in live patients. Even though Wright has used cadaveric specimens, the significant difference might be due to racial differences between the populations (Irish and Indian) of the study.

Table 7. Comparison of the diameter of the branches of the aortic arch in various studies.

Diameter (mm)	Wright NL[67] (n=100)	Kahraman[53] (n=25)	This study (n=100)
R1	12.5±1.25	12.07±1.58	9.7±1.80*
R2	9.5±0.76	-	8.5±1.59*
L1	7.5±2.09	7.15±0.92	6.79±1.18**
L2	5.5±1.30	6.63±1.14	5.7±1.18
S1	10.0±2.15	9.04±1.74	7.62±1.8*
S2	7.5±1.05	-	6.37±1.57*
T1	3.0±1.40	-	4.25±2.39*
T2	7.0±4.12	-	7.49±2.87

Values are mean ± SD. *P<0.0001 when compared to the values by Wright NL. **P<0.01 when compared to the values by Wright NL. R1 – origin of BCT, R2 – 15 mm distal to R1, L1 – origin of LCCA, L2 – 15 mm distal to L1, S1 – origin of LSCA, S2 – 15 mm distal to S1, T1 – distance between adjacent margins of R1 and L1, T2 – distance between adjacent margins of L1 and S1.

The diameters of the branches of the aortic arch (except the diameter of left common carotid artery 15 mm distal to its origin) of the present study differ significantly (p<0.0001) from the study conducted by Wright NL (Table 7). The aortic arch is a dynamic structure during life. Left ventricular ejection produces changes in circumference and diameter of aorta which may correlate quite closely with intra-aortic pressure changes.[71] The values given here refer to measurements on cadaveric material and does not account for the distensibility of the aorta. This may account for the lower values seen in this study when compared to other studies.

Strengths of the study

1. The presence of a common ostium for the brachiocephalic trunk and the left common carotid artery was confirmed by making silicon luminal casts of the aortic arch.

2. Taper ratio of the aortic arch was calculated.

Limitations of the study

1. Since measurements were made on cadaveric specimens they do not account for the elasticity of the aorta.

Future directions

Further studies on the dimensions of the aortic arch and its branches with CT in live individuals measured using electronic callipers will enable us in designing stents with tapered design for various endovascular surgeries.

CONCLUSION

The frequency of the various branching patterns observed in hundred cadaveric specimens are Type I – 79%, Type II – 14%, Type III – 4%, Type IV – 2% and Type IX – 1%.

The diameter (mean ± SD, in mm) of the aortic arch and its branches at different points are 20.14 ± 2.84 (ascending aorta 25 mm proximal to the origin of brachiocephalic artery), 19.69 ± 2.72 (arch proximal to the origin of brachiocephalic artery), 17.69 ± 2.74 (arch distal to the origin of brachiocephalic artery), 16.49 ± 2.63 (arch distal to the origin of left subclavian artery), 15.57 ± 2.48 (descending aorta 25 mm distal to the origin of left subclavian artery), 9.7 ± 1.80 (origin of brachiocephalic trunk – R1), 8.5 ± 1.59 (15 mm distal to R1), 6.79 ± 1.18 (origin of left common carotid artery – R2), 5.7 ± 1.18 (15 mm distal to L1), 7.62 ± 1.8 (origin of left subclavian artery – S1), 6.37 ± 1.57 (15 mm distal to S1), 4.25 ± 2.39 (distance between adjacent margins of R1 and L1) and 7.49 ± 2.87 (distance between adjacent margins of L1 and S1).

The diameter of the aortic arch decreases significantly ($p<0.05$) from its proximal to distal end in both normal and variant aortic arches.

The mean taper ratio (mean ± SEM) is 22.57 ± 0.67% and the taper ratio of the normal and variant groups does not differ significantly.

The diameter of the branches of aortic arch did not differ significantly between the various anomalies except in two instances viz., the diameter of brachiocephalic trunk at its origin and that of left common carotid artery 1.5 cm distal to its origin, which are significantly greater ($p<0.05$) in specimens with left vertebral artery as an additional branch of the aortic arch when compared to other groups.

SUMMARY

Aortic arch is a dynamic structure showing a wide variation in its branching pattern which are often associated with anomalies of cerebral vasculature and other cardiovascular anomalies. The presence of anomalous branches decides the surgical approach, increases the failure rate and neurological complication in stenting procedures. The diameters of the aortic arch decreases as it gives off its branches which is important in designing tapered modifications of stents in endovascular repair of aortic dissection. Even though variations in branching pattern and anomalies are documented in the literature, very few data are available regarding the dimensions of normal and anomalous arch and its branches. Therefore we intend to study the variations in branching pattern of arch of aorta and dimensions of the arch and its branches in cadaveric specimens by gross dissection.

Specimens from hundred adult human cadavers aged above 20 years of both sex were obtained from the Departments of Anatomy and Forensic medicine, Thanjavur Medical College, Thanjavur. They were fixed and dissected to observe the branching pattern of aortic arch, which was confirmed by examining the ostium on the luminal side or by making silicon luminal casts of the aortic arch. The diameters of the aortic arch and its branches were also measured at different points.

The frequency of the various branching patterns observed are Type I – 79%, Type II – 14%, Type III – 4%, Type IV – 2% and Type IX – 1%. The diameter of the aortic arch was found to decrease significantly ($p<0.05$) from its proximal to distal end in both normal and variant branching patterns. The mean

taper ratio is 22.57 ± 0.67% and the taper ratio did not differ significantly between the normal and variant groups. The diameter of aortic arch at different points differ significantly ($p<0.001$) from the values measured by Wright NL and Hager. While Hager studied live patients which could account for the difference, the difference in cadaveric specimens used by Wright could be due to racial differences between Irish and Indian populations. Further studies on the dimensions of the aortic arch and its branches in live individuals will enable us in designing stents.

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Abbreviations

ANOVA – Analysis of variance

BCT – Brachiocephalic trunk

chr – Chromosome

cm – centimetre

CoA – Coarctation of aorta

CT – Computed tomography

DA – Ductus arteriosus

DSA – Digital subtraction angiography

Fr – French gauge

LCCA – Left common carotid artery

LSCA – Left subclavian artery

MDCT – Multidetector computed tomography

MIP – Maximum intensity projection

mm – millimetre

MRI – Magnetic resonance imaging

PDA – Patent ductus arteriosus

SD – Standard deviation

SEM – Standard error of mean

ToF – Tetralogy of Fallot

VATS – Video assisted thoracoscopic surgery

VSD – Ventricular septal defect